Water Quality Indicators for Reservoirs: Proceedings of a Workshop

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BACKGROUND: Effective environmental management is an emerging theme for the 21st century for all federal agencies. The Government Performance and Review Act (GPRA) of 1993 requires that all federal agencies, beginning with the 1999 fiscal year budget request, submit to the Office of Management and Budget and to Congress a strategic plan that establishes project goals and objectives. GPRA also requires implementation of an annual plan with performance measures to evaluate the effectiveness of management strategies in achieving these goals and objectives. This increased emphasis on performance-based management means that more effective monitoring programs are needed. Monitoring is the only feasible approach for evaluating the success and performance of project management strategies over time. However, the monitoring program will only be as effective as the measures selected to indicate environmental condition or change.

The Intergovernmental Task Force on Monitoring Water Quality (1995) defined environmental indicators as "... measurable feature or features that provide managerially and scientifically useful evidence of environmental and ecosystem quality or reliable evidence of trends in quality." Selecting the appropriate indicators for monitoring in U.S. Army Corps of Engineers reservoirs is critically important in evaluating the effectiveness of project management and operational performance.

Over the past 20 years, the environmental focus has broadened from local-scale, site-specific impacts to ecological issues at watershed, regional, and, in some instances, global scales. Loss of biotic diversity, global warming, inter-basin water transfers, cumulative basin impacts, increased population growth and changing demographics, and other large-scale issues are becoming increasingly important in all aspects of water resources management. There is a critical need for monitoring programs that incorporate scientifically defensible, cost-effective indicators to assess the effects of management strategies at multiple scales.

The Environmental and Water Quality Indicators Workshop was conducted in conjunction with the Corps' 12th Water Quality Seminar held in Kansas City, Missouri, in June 1998, as a means to initiate a Corps-wide discussion of these needs. This technical note summarizes discussion from the workshop and provides additional insight for incorporating environmental and water quality indicators in performance-based monitoring programs for Corps reservoirs.

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MANAGEMENT-INDICATORS INTERACTION FRAMEWORK: Asking the right questions is the key to success in any management study or program. Bardwell (1991) cites a study that indicates that about 90 percent of real-world problem-solving activities is spent:

a. Solving the wrong problem.

b. Stating the question so it cannot be answered.

c. Solving a solution.

d. Stating the question too generically.

e. Trying to get agreement on the answer before there is agreement on the questions.

For monitoring programs to select the appropriate indicators and provide information that contributes to management decisions, it is critical that the management questions and needed information are clearly articulated and understood.

Five fundamental questions, each of which can be associated with virtually all environmental management efforts, are listed below.

a. What is the problem and how big is it (both in magnitude and extent)? . . . . . . Condition Indicator

b. Is it getting better or worse? . . . . Trend Indicator

c. What's causing the problem? . . . . Diagnostic Indicator

d. What can be done about it? . . . . Management Indicator

e. Is management making a difference? . . . . Performance Measure

Answers to these questions, while requiring somewhat different information, help to frame management efforts when considered together. This information can be summarized or incorporated in the form of a series of related indicators. These include indicators of conditions, trend, diagnosis, management, and performance. A general framework to address these five questions and interactions among the five resulting types of indicators is shown in Figure 1.

Problems or issues arise because desired societal values or project purposes do not appear to be satisfied by the existing condition at the project. One of the first steps, then, is to identify the relevant societal values and purposes associated with each project (Figure 1). Next, management endpoints need to be defined that relate directly to these societal values. Management endpoints typically include considerations of socioeconomic indicators (e.g., capital cost, O&M cost, visitor satisfaction) in addition to environmental or condition indicators. Not all management endpoints are directly or easily measurable. Therefore, surrogate indicators are selected to help link the management endpoints to measurable and observable conditions in the reservoir or watershed. These indicators might be condition indicators or diagnostic indicators (Figure 1). The key is that these indicators can be related to the management endpoints. Finally, performance measures need to be developed that can be used to determine how well societal values and project purposes are being achieved (Figure 1). These performance measures relate to management endpoints and, ultimately, to the effectiveness of the monitoring program in providing use-

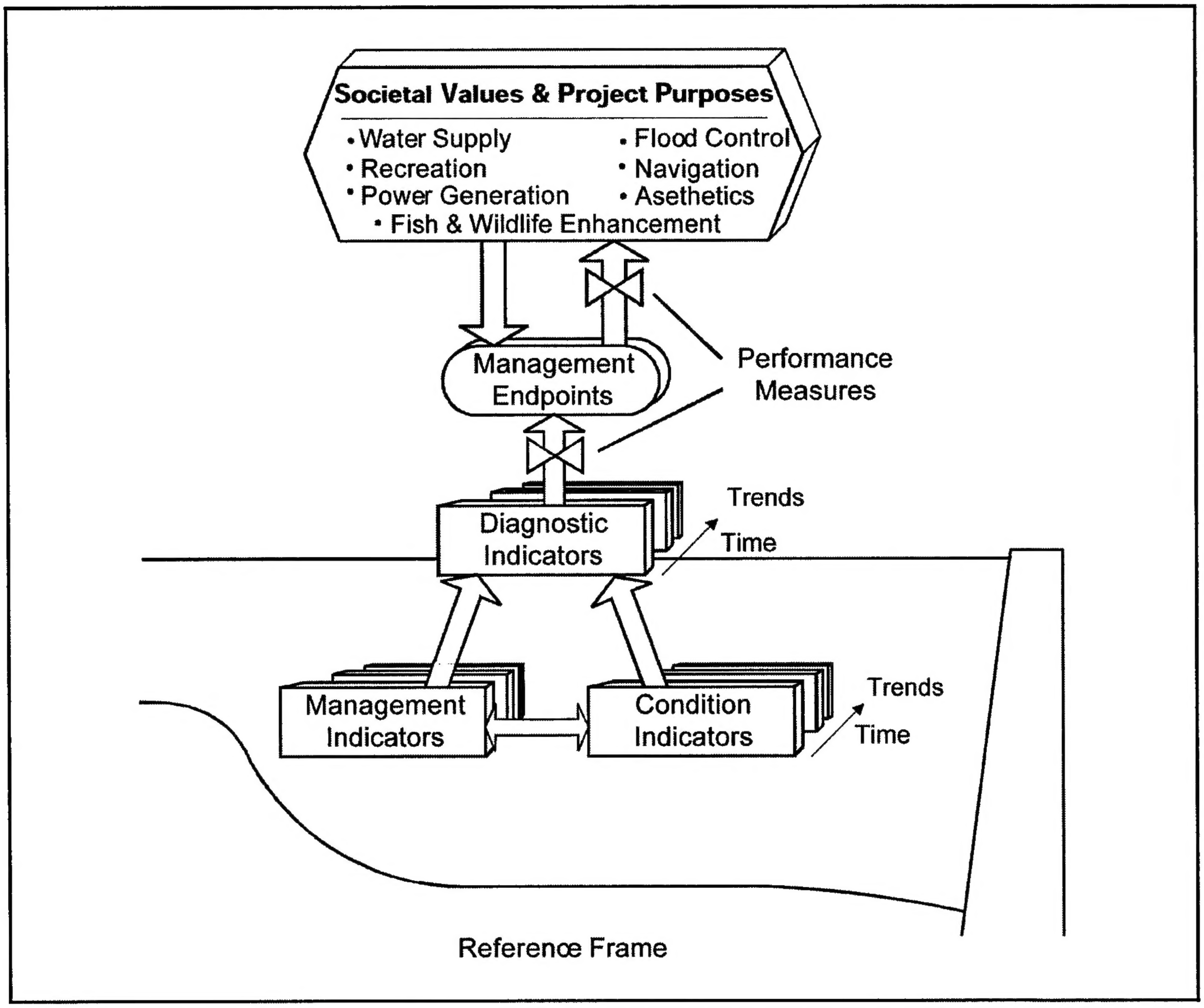

Figure 1. General categories and relationships among reservoirs environmental indicators. Management performance is compared with desired and achievable (reference) conditions

ful and relevant information for making management decisions. Management endpoints and indicators are discussed in detail below.

Management endpoints should relate directly to project purposes or desired societal values (Figure 1). Examples include providing sufficient storage for flood waters and water supply, propagating sustainable fisheries, and providing recreational opportunities and an aesthetic environment. These endpoints, where possible, should be quantitatively expressed. For example, management endpoints might be to provide 25,000 ac-ft of storage for spring flooding, provide up to 40,000 ac-ft for water supply, sustain a largemouth bass fishery within ± 30 percent of its carrying capacity, sustain recreational visitation between 1.5 and 3 million visitor days/year, and maintain shorelines with less than 1 item of trash/400 linear feet, and water transparency of at least 2 m during the summer season.

Management indicators gauge attainment of management endpoints and allow interpretation of measures of condition and trends or of diagnostic information (see below) within the context

established by project purposes or desired societal values. While many management indicators can be measured directly, others, such as a sustainable bass fishery or water transparency, require surrogate measures of reservoir condition (Figure 1).

Condition indicators are ecological response or exposure measures or metrics that can be related to management endpoints. For example, the standing stock of largemouth bass measured during a fall cove rotenone or shocking census is one indicator of reservoir condition and a sustainable fishery. Largemouth bass biomass can be related to the management endpoint of fisheries enhancement. Another condition indicator might be chlorophyll concentrations measured during the summer recreational season. Condition indicators based on measures of exposure to stressors can also be used to indicate ecological condition. For example, contaminant concentrations in finfish or shellfish can be used to evaluate reservoir environmental condition and provide a link between management and condition indicators and between condition and diagnostic indicators (Figure 1). In general, *trend indicators* arise from monitoring condition indicators through time.

Diagnostic indicators provide information and insight into causal mechanisms or processes that influence or contribute to reservoir responses (condition or trends). Diagnostic indicators can be related to physical (flow, temperature, suspended solids), chemical (total phosphorus, nitrate-nitrogen, dioxin, cadmium concentrations), biological (zebra mussels, *Pfesteria* sp., macrophyte distribution) or habitat (sediment composition, shoreline structure) characteristics (Table 1). Diagnostic indicators also can reflect changes in watershed land use or land cover, demographic changes, or similar circumstances or factors that are contributing both to the existing condition and historical trends in that condition.

Performance measures are quantitative statements that evaluate how well management practices are achieving or attaining societal goals or project purposes. Performance measures provide a benchmark for comparison with management endpoints or indicator metrics or measures. Performance measures should incorporate the variance expected in the management endpoints and realistically reflect desired management goals and societal values. For example, the performance measures for a sustainable largemouth bass fishery might be a harvest of 35 lb/acre/year and a cove rotenone estimate of at least 65 lb/acre/year. The performance measure for aesthetic condition might be that no more than 10 percent of the Secchi depth measures are less than 1 m during the year and that less than 20 percent of observed chlorophyll concentrations in the lower half of the reservoir are greater than 30 ug/L.

Together, management endpoints, indicators, and performance measures allow managers to successfully link problem identification and problem solution. With information on current condition, trends, and underlying causal factors, management strategies or practices to protect, maintain, or improve the reservoir ecosystem and its responses can be implemented and evaluated.

OVERVIEW OF COMMONLY USED WATER QUALITY INDICATORS: Limnologists, aquatic ecologists, and water quality managers have employed a range of indicators as means to gauge environmental condition or changes in environmental condition. These include (a) physicochemical indicators, (b) nutrient and chemical indicators, (c) biological indicators, and (d) integrative indicators, all of which are applicable to Corps reservoirs.

Table 1
Selected Environmental Indicators, By Category, Discussed at the Environmental and Water Quality Indicators Workshop*

Indicator Categories			
Condition/Trends	**Diagnostic**	**Management**	**Performance Measures**
Secchi depth Chlorophyll *a* concentration Fish health Fish community composition Algae species Dissolved oxygen Bacteria (Fecal coliform)	Total phosphorus Nitrate-N Ammonia-N Dissolved oxygen Nutrient loading/ mass balance Temperature Flow Suspended solids	Number of visitation days Park/camping fee revenue NPDES permit violations O&M costs Hydropower revenues Storage loss Taste & odor problems	Reduction in visitor/user complaints Increase in visitation days Following reservoir rule curves No regulatory violations Meeting low flow or minimum releases

* Note that indicators may provide information in more than one category.

Physicochemical Indicators. Physicochemical indicators are based on measures of physical (e.g., temperature) or chemical (e.g., dissolved solids and dissolved oxygen concentrations) attributes of reservoir water quality. The data upon which these indicators are based are relatively inexpensive and simple to collect. However, they may provide a valuable gauge of current water quality conditions and insight to the importance of complex processes influencing water quality. For instance, recognizing the expected balance between the production and consumption of oxygen in ecological systems led to the early use of oxygen depletion in lake bottom waters to estimate oxygen budget imbalances due to eutrophication (Hutchinson 1957).

Another well-known example is the morphoedaphic index (MEI; Ryder 1965). The MEI is an empirically based indicator of potential fish production that relies on the observed correlation between total dissolved solids divided by mean depth and fish yield. Under the convention established by Ryder (1965), fish yield is expected to increase with increases in the MEI.

Nutrient and Chemical Indicators. These indicators measure the concentrations of important nutrients and chemicals. They may be measured as ambient concentrations or as potential concentrations, and are often used to judge compliance, assess potential toxicity, or evaluate symptoms of eutrophication. Ambient nutrient concentrations, particularly phosphorus and nitrogen, have long been used as gauges to eutrophication in lakes and reservoirs (e.g., National Academy of Sciences 1969). For instance, Ryding and Rast (1988) present boundaries for mean annual ambient phosphorus and nitrogen concentrations for reservoirs of differing trophic status, since both nutrients are influential in determining algal concentrations in surface waters. Ratios of these two nutrients are also suggested as indicators of relative nutrient availability and potential limitation, both of which are important management considerations. It is important to note that EPA and the states are currently developing nutrient criteria and standards for lakes and reservoirs (U.S. Environmental Protection Agency 1998).

The potential for changes in ambient nutrient concentrations, and subsequent changes in algal chlorophyll, have also been the focus of efforts to develop effective water quality indicators. Changes in average nutrient concentrations have been successfully predicted using relatively simple empirical relationships or models. Perhaps best known are those developed for total phosphorus (e.g., Vollenweider 1968, 1976). Simple models can be used to establish critical loading rates above which lakes would be expected to exhibit excessive chlorophyll concentrations. The management implications of defining loading limits are obvious.

A similar concept currently in use is that of determining total maximum daily load (TMDL; U.S. Environmental Protection Agency 1991). The TMDL process provides a mechanism for regulators to establish limits on allowable loads from the watershed as a means to protect water quality. In establishing these limits, a relationship between load and the resulting impact (e.g., unacceptable change in ambient concentration) is assumed.

Biological Indicators. Many environmental management problems are framed in the context of impacts to organisms or to biological communities. While the pathway or mode of impact is seldom fully understood, changes to organisms or communities are observable and measurable. The absence of an organism known to be intolerant to a particular type of pollutant may indicate unacceptably high levels of the pollutant. Conversely, the presence or abundance of a pollutant-tolerant organism may also indicate that the pollutant is present. Clearly, such indicators are not unambiguous, and supplemental information is always required.

Less dramatic biological changes are also important. The loss of one or more species or ecologically functional groups (e.g., piscivorous fish) from a community may have long-term implications for environmental quality. Such changes in species composition have traditionally been addressed using a variety of indices of abundance, evenness, similarity, or diversity. While abundance is a simple accounting of the numbers of individuals present for each species, indices of evenness or similarity describe the relative distribution of individuals across species within a community or habitat. Diversity measures account for the number of species present, as well as the abundance of individuals of each species, and compute a single index value. Perhaps best known of the diversity indices is the Shannon Index (based on Shannon and Weaver (1949)), which increases in value as the number of species and their relative evenness increase.

These indicators are often applied in a before-and-after or with-and-without-pollution comparison. Wilhm (1967) illustrates marked changes in stream benthic species diversity from immediately above to below a sewage outfall. In other applications, biological indicators have been applied to non-impacted areas or pre-pollution time periods as a means to gauge current conditions or conditions following introduction of a pollutant or other environmental stress.

Integrative Indicators. The complexity of environmental problems and the limitations of using a single indicator have prompted the development and application of indicators that integrate information across a range of attributes of environmental systems and/or different levels of biological organization.

Limnologists have long used broadly defined terms to describe complex changes associated with eutrophication. For example, eutrophic lakes are characterized as having high nutrients and al-

gal abundance, while the opposite is true for oligotrophic lakes. Carlson (1977) developed the Trophic State Index (TSI), which integrates information about nutrient (phosphorus) concentration, chlorophyll, and transparency (Secchi disk depth), allowing water quality managers to quantify these commonly applied terms. The TSI is empirically based and uses a scale for increasing the degree of eutrophy from 0 to 100.

The Index of Biotic Integrity (IBI; Karr et al.(1986)) recognizes the importance of interactions among five classes of factors important to aquatic biota: energy, chemical constituents, habitat structure, hydrology, and interactions between organisms. The U. S. Environmental Protection Agency (in press) has recently developed guidance for establishing biological criteria and biologically assessing lakes and reservoirs. The procedure involves the use of a multimetric bioassessment based on data collected as part of a multi-tiered sampling program. The sampling tiers include land-use assessments, water chemistry, TSI values and macrophyte surveys (Tier 1), and biological assemblages (e.g., phytoplankton, zooplankton, benthos, fish; Tier 2). Composited metric values are then compared to those for reference lakes and reservoirs (see section titled "Frame of Reference").

Larger-scale, integrated indicators applicable to reservoir management are also being developed (e.g., watershed condition indices that rank watershed condition as a function of disturbance and development). Landscape indicators can provide insight into watershed land cover patchiness, connectedness, fragmentation, and similar patterns. These indicators or metrics can help determine not only watershed condition, but also the implications for riparian, stream, and river conditions, all of which can impact reservoir quality. Similar integrative metrics should be developed for reservoirs based on watershed/reservoir units.

SUGGESTED WATER QUALITY MANAGEMENT INDICATORS FOR CORPS RESERVOIRS: Workshop participants identified several water quality indicators for each major indicator category (i.e., management, condition, diagnostic, and performance measures; Table 1). Only a select number of ecological and environmental indicators are currently being, or proposed to be, monitored in Corps reservoirs. Information on many of the management indicators and performance measures can be constructed from existing records for Corps reservoirs. Other indicators will need to be added to existing monitoring programs. However, the indicators in Table 1 can be used to illustrate the linkages among management, condition, and diagnostic indicators, how these indicators relate to management endpoints, and how reservoir management is integrated with watershed management.

Reservoir management cannot be divorced from watershed management. As stewards of the reservoir, the Corps should forge partnerships with the agencies, organizations, and private sector in developing integrated watershed/reservoir management programs. Watershed activities clearly affect reservoir quality, but changes in reservoir quality also can indicate needed changes in water-shed management. For example, assume management endpoints are to provide suitable water for domestic supply, maintain recreational visitation, and create an aesthetic environment. Management indicators that relate to these endpoints are storage loss, number of visitation days and taste and odor problems (Table 1). Condition and diagnostic indicators that are linked to the management indicators include existing reservoir storage volume allocated to domestic water supply, chlorophyll concentrations, Secchi disk transparency, and total phosphorus concentrations

(Table 1). Domestic water quantity can be monitored by tracking the remaining volume of water allocated for drinking water while domestic water quality can be evaluated by considering chloropyll concentrations both for taste and odor potential as well as for total trihalomethane precursor potential (TTHMP). Recreational visitation also will depend, in part, on the occurence of nuisance algal blooms and water clarity. If nuisance algal blooms occur (e.g., chlorophyll concentrations greater than 30 ug/L), both water quality and aesthetics (i.e., water clarity) will be affected. Increased nutrient concentrations or an increase in total phosphorus concentrations or loads can indicate that nutrients might be contributing to nuisance algal blooms. Secchi depth transparency also can provide insight into whether decreases in transparency are correlated with algal blooms. If there is no correlation between increased chlorophyll and decreased Secchi depth, erosion and inorganic sediment transport into the reservoir might be the stressor, which also can affect recreational enjoyment and aesthetics. Performance measures might indicate that management practices are not achieving desired results because TTHMP has exceeded 100 ppb (e.g., regulatory violation - Table 1), more than 10 percent of the Secchi depth measurements are less than 1 m, more than 20 percent of the chlorophyll concentrations exceeded 30 ug/L, and recreational visitation has decreased below 1.5 million visitor days. Increased nutrient concentrations might indicate that watershed nutrient loading has increased. Cooperative investigations with watershed partners can assist in identifying the critical management areas in the watershed for implementation of best management practices and potential in-lake management practices.

Additional indicators will be required to develop an integrated picture of watershed-reservoir interactions. Since episodic events can be missed in monthly monitoring programs and toxic constituent concentrations can be below detection limits using traditional methods, new indicators and approaches are needed that provide this type of information. For example, when benthic communities contain primarily organisms that tolerate low pH, acid mine drainage or acid rain runoff may be entering the reservoir during storms, even though base-flow monitoring indicates circumneutral pH values. Elevated mercury concentrations in largemouth bass indicate mercury methylation is occurring in a reservoir, even if mercury concentrations in the water are less than detection limits. Fish, benthos, phytoplankton, and other biological assemblages integrate both short- and long-term stressors in the system. In the future, additional emphasis should be placed on biological and integrative indicators.

Regardless of the Corps division, reservoir type, or problems and issues, management endpoints must be explicitly stated and linked to the societal values and project purposes, the endpoints must be anchored explicitly to condition and diagnostic indicators, and performance measures must be established. Without this, monitoring information will not contribute effectively to management decisions. In addition, performance measures must be formulated to assess the effectiveness of management practices in maintaining, enhancing, protecting, or restoring reservoir quality. Ideally, a conceptual model or simple box-and-arrow diagrams would be developed to show the linkages among indicators, endpoints, and performance measures. These techniques are effective in documenting why various indicators are being monitored, and how they relate to management decisions. This workshop initiated this process and an ongoing dialog between managers and assessors monitoring reservoir condition.

FRAME OF REFERENCE: Developing performance measures without a frame of reference is difficult. For reservoirs, which are man-made systems without a natural counterpart for reference,

the task is even more difficult. Reservoirs were formed by impounding lotic or flowing systems. Thus, unlike natural lakes, impounded or lentic systems have limited pre-existing conditions against which to compare the current condition. Also, water control and water quality management practices typically differ for reservoirs within the same basin or on the same river. In addition, because reservoirs are relatively new features of the landscape and are located on large-order streams, they are impacted to some degree by anthropogenic influences. As a result, there are essentially no nonimpacted reservoirs to define reference conditions. There are, however, "least-disturbed" reservoirs that might provide a reasonable frame of reference.

There are two approaches to providing a frame of reference for reservoirs. The first is to develop frequency distributions of reservoir characteristics and environmental indicator values and to use these distributions to provide a reference for a specific reservoir. The second approach is to use empirical relationships or models based on first principles to determine expected or attainable limnological conditions for a specific reservoir.

DISTRIBUTION OF RESERVOIR CONDITIONS AND CHARACTERISTICS: Cross-sectional analyses of observed water quality data provide a sound empirical approach to establishing a national or regional frame of reference for lakes and reservoirs. Heiskary, Wilson, and Larson (1987) suggested that management goals for lakes in Minnesota could be based on ecoregions (Omernik 1987) and a state-wide assessment. Analyses for Corps reservoirs might logically be based on Corps division or district boundaries. While significant for administrative and management purposes, divisional or district boundaries are based primarily on major hydrologic boundaries (i.e., major river basins), and as such, provide a reasonable partitioning for defining a reference framework.

As an example of this approach, water quality data collected at Corps reservoirs during the period 1973-1977 as part of the National Eutrophication Survey (U. S. Environmental Protection Agency 1978) were summarized by Corps division (see Figure 2 for the nationwide distribution of Corps reservoirs relative to division boundaries). Data for surface waters (depth $\leq$ 5 m) were summarized by computing reservoir means for the growing season (May-Oct) for total phosphorus and chlorophyll *a* concentration. While exhibiting considerable within-division variability, between-division differences were apparent. Total phosphorus concentrations were, on average, highest among Mississippi Valley Division (MVD) and Southwest Division (SWD) reservoirs, and lowest for Northwest Division (NWD) reservoirs (Figure 3). Similarly, degrees of variability and between-division patterns were observed for chlorophyll *a* concentrations (Figure 4).

Such cross-sectional assessments may provide the best approach to developing a reference framework for Corps reservoirs. Using current and historical data, division water resource personnel have the opportunity to delineate reference conditions in the context of a region, watershed, or administrative area. Current conditions can be viewed in a historical context to assess trends or compare with management targets. Similar assessments can be performed across years for individual reservoirs to assess relative condition and to better allocate management resources.

EMPIRICAL RELATIONSHIPS, MODELS, AND ATTAINABLE CONDITION: Both simple and complex models provide insight into potentially important processes and how these processes affect reservoir quality. Simple models range from order-of-magnitude or "back-of-the-envelope"

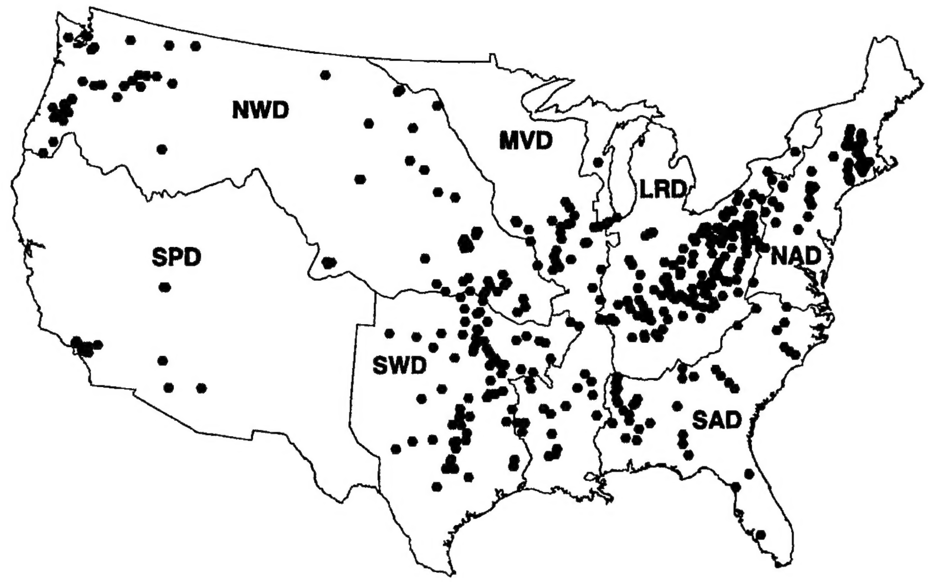

Figure 2. Map of the geographic distribution of Corps reservoirs and Corps division boundaries. Abbreviations indicate division name: LRD, Great Lakes and Rivers Division; MVD, Mississippi Valley Division; NAD, North Atlantic Division; NWD, Northwest Division; SAD, South Atlantic Division; SPD, South Pacific Division; and SWD, Southwest Division.

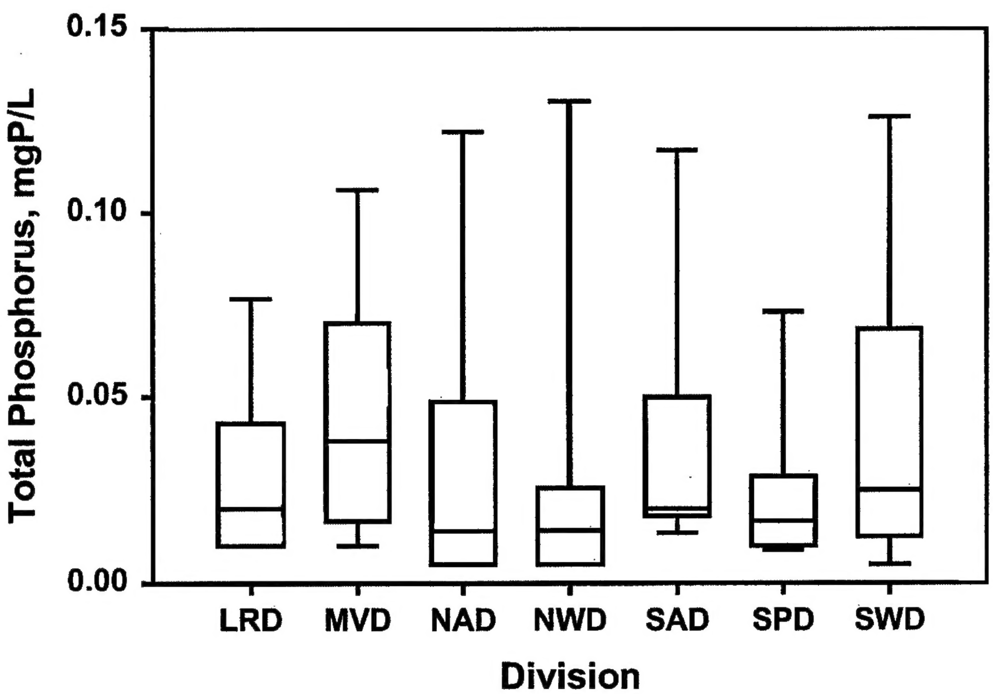

Figure 3. Frequency distribution of reservoir mean growing season (May-Oct) total phosphorus concentration (mgP/L) for Corps divisions. Based on National Eutrophication Survey data (U.S. Environmental Protection Agency 1978)

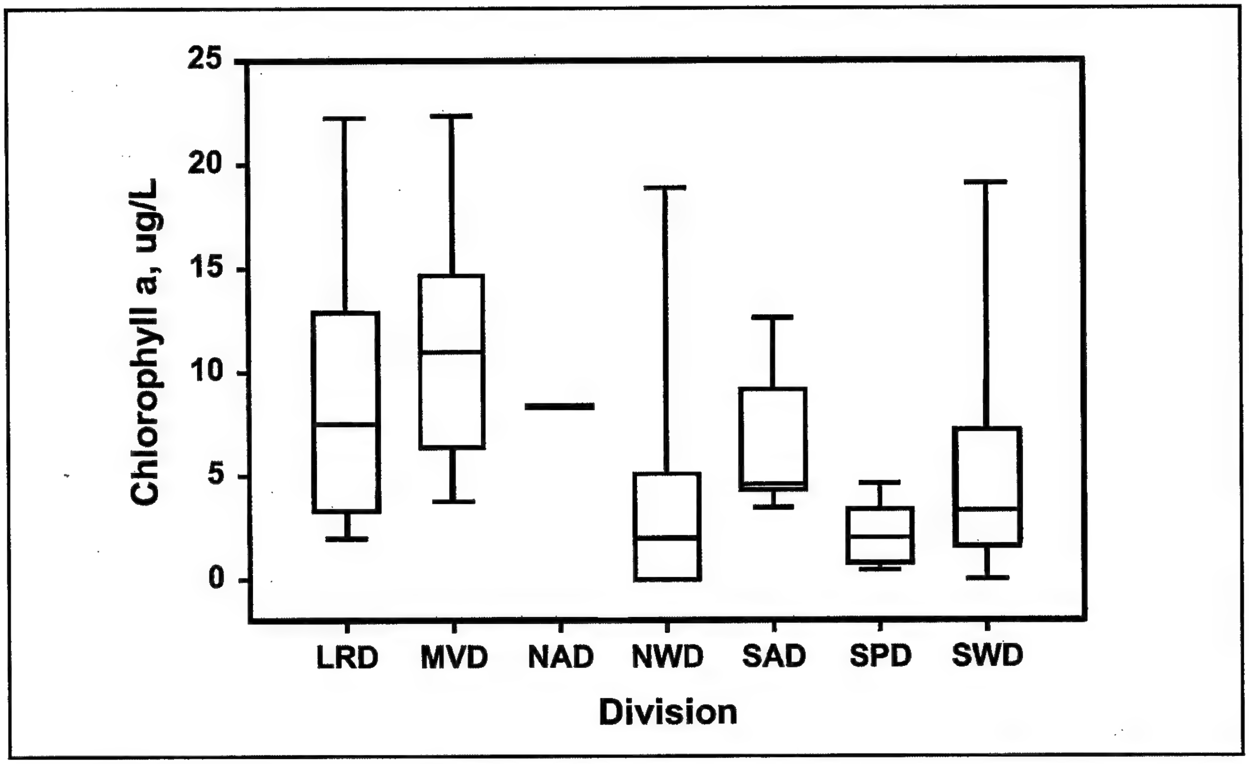

Figure 4. Frequency distribution of reservoir mean growing season (May-Oct) chlorophyll *a* (corrected) concentration (μg/L) for Corps divisions. Based on National Eutrophication Survey data (U.S. Environmental Protection Agency 1978)

estimates to PC-based modeling software that incorporates equations formulated from cross-sectional reservoir data. Complex models, which may be based in part on first principles and often include both hydrodynamic and water quality considerations, allow estimation of expected conditions for reservoirs. Understanding expected reservoir condition can provide a frame of reference for management.

Order-of-magnitude calculations (such as relative depth, areal erosion, or residence time) can provide insight into the relative importance of various reservoir processes in controlling reservoir quality. These estimates can also be useful in developing and evaluating reservoir quality management strategies (e.g., Håkanson 1997). Several useful order-of-magnitude estimates are shown in Table 2. Order-of-magnitude estimates contribute to a reference frame by helping bound the range of expected reservoir conditions. For example, aspect ratios (comparison of length to average width) indicate whether longitudinal or lateral gradients might be expected to dominate in a water body. An aspect ratio (L/W) greater than 4:1 indicates longitudinal water quality gradients would be more important than lateral water quality gradients (Jirka and Harleman 1979). Areal erosion estimates represent the proportion of the lake bed area that might be exposed to erosion (Håkanson 1982). As the areal erosion estimate increases, erosion and sediment transport from the shoreline into the reservoir might be expected to increase, which can impact water quality, aquatic vegetation, and nursery areas for fisheries. While these estimates are "back of the envelope," they can provide a reference frame of expected reservoir conditions, especially when integrated with information from other tools and sources such as em-

Table 2
Order-of-Magnitude Estimates of Selected Reservoirs Characteristics Based on Hydrology and Reservoir Attributes

Reservoir Attributes	
Volume, $\forall$ (m^3)	
Surface area, SA (km^2)	
Watershed area, DA (km^2)	
Length, L (km)	
Length of shoreline, L_s	
Mean width, W (km) SA/L	
Maximum depth, Z_m (m)	
Mean depth, Z (m), $\forall/SA$	
Order of Magnitude Estimates	
Mean depth/maximum depth, Z/Z_m	
Drainage area/surface area, DA/SA	
Aspect ratio, L/W	
Shoreline development ratio	$L_s / 2\sqrt{\pi SA}$
Relative depth	$50 Z_m \sqrt{\pi / SA}$
Areal erosion	$52 * \left\lvert \sqrt{SA} / Z_m - 0.2 \right\rvert * Z_m / 3Z * \log\left(60.6 * Z / \sqrt{SA}\right) + 19.3$
Residence time, τ (yr)	$\forall / Q$
Densimetric Froude Number, Fd	$Q * L / \left(V * \sqrt{g * Z * \Delta\rho / \rho}\right)$
Single storm flushing ratio	$Q_s / \forall$
Depth at plunge point (m)	$\left\{Q^2 / \left[W_c^2 * F_P^2 * g * (\Delta\rho / \rho)\right]\right\}^{1/3}$

Note:
- Q = average annual total inflow (m^3/s)
- Q_s = largest daily total inflow on record for May-Oct (m^3/s)
- $\Delta\rho$ = density difference between inflow and lake surface water (kg/m^3)
- ρ = density of surface water in lake (kg/m^3)
- g = gravitational constant 9.8 m/s^2)
- W_c = width of zone of conveyance at plunge point (m)
- F_P = critical densimetric Froude number (assumed to be 0.4 based on literature)
- Z_s = average Secchi depth (m)

pirical models, dynamic model results, special studies (e.g., sediment bioassays), and monitoring data.

Empirically based models have become important tools for understanding lake and reservoir water quality relationships, and for developing management plans, particularly related to eutrophication (Reckhow and Chapra 1983). These may take the form of bivariate regressions or simple steady-state models. For instance, relationships between nutrient availability (particularly phosphorus), and algal chlorophyll are well-documented and have frequently been used to "predict" changes in chlorophyll concentration following decreases or increases in phosphorus concentration (Cooke et al. 1993).

The Corps has developed several models that predict a number of reservoir attributes. BATHTUB (Walker 1996) is a steady-state model that estimates such eutrophication-related attributes as hypolimnetic oxygen deficit, Secchi transparency, total phosphorus and chlorophyll concentrations, and the probability of various trophic states. More detailed estimates are provided by mechanistic models, such as the two-dimensional model CEQUAL-W2 (Cole and Buchak 1995), which incorporates both hydraulic and water quality considerations, and is time-varying. These and other models can be used to identify factors contributing to current reservoir condition, evaluate potential reservoir responses to various management strategies, and provide a "least-disturbed" reference frame for background conditions assuming minimal watershed disturbance. These empirical estimates can be used to determine the difference between the current reservoir condition and the "least-disturbed" reservoir condition.

CONCLUSIONS AND RECOMMENDATIONS: When properly applied, environmental indicators provide valuable insight into complex environmental problems and can be used to effectively support the management-decision process. However, indicators are based on limited data and prudent choices must be made in their selection, application, and interpretation. Managers must ensure that indicators are relevant to management issues and target appropriate attributes of the environment. In most cases, this will be an iterative process in which indicators are evaluated in the context of results from previous applications and with consideration of the informational needs of emerging management issues.

Indicators must also be accepted by all participating parties for management efforts to be successful. This is particularly true for the Corps since management concerns for reservoirs are often geographically expansive and management efforts will cross administrative boundaries. Corps water quality personnel must actively participate in debates among watershed partners concerning management issues and the choice, use, and interpretation of indicator measures and metrics.

The identification of realistic and appropriate water quality references is critical to successful and meaningful application of water quality indicators for Corps reservoirs. Since they cannot be easily compared to natural lakes, identifying appropriate references for reservoirs will be more difficult. Suggestions are frequency analyses of water quality data, the use of simple empirical models based on observed relationships or the use of mechanistic water quality models. In either application, the Corps must develop a comprehensive national or regional water quality

database. Such a database will allow the development of a frame of reference that implicitly acknowledges differences between natural lakes and reservoirs.

The system of indicators discussed here links problem identification to management activities and performance, and is an initial effort to establish appropriate water quality indicators for Corps reservoirs. For reservoir management to achieve desired societal and project objectives in the 21st century, the management perspective must change from merely viewing reservoirs as engineered water control systems to considering them as managed ecosystems.

The classical definition of water quality is the physical and chemical environment in a water body, excluding biology. However, many of the emergent properties of aquatic ecosystems are biological and ecological. As such, biological and integrative indicator development has been an active area of research during the 1990's and will continue into the next century. EPA, states, and other regulatory agencies are currently formulating biological and nutrient criteria for aquatic ecosystems, including reservoirs. Therefore, the Corps must become an active partner in this development or accept criteria developed and imposed by others, knowing that such criteria may not be fully appropriate for the management of reservoirs.

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Table 1. Selected environmental indicators, by category, discussed at the Environmental and Water Quality Indicators Workshop. Note that indicators may provide information in more than one category.

Indicator Categories**Condition/TrendsDiagnostic**Secchi DepthTotal phosphorusChlorophyll a concentrationNitrate-NFish healthAmmonia-NFish community compositionDissolved oxygenAlgae species Nutrient loading/mass balanceDissolved oxygenTemperatureBacteria (Fecal coliform)FlowSuspended Solids**ManagementPerformance Measures**Number of visitation daysReduction in visitor/user complaintsPark/camping fee revenueIncrease in visitation daysNPDES permit violationsFollowing reservoir rule curvesO & M costs No regulatory violationsHydropower revenuesMeeting low flow or minimum releases Storage lossTaste & odor problems**Table 2.** Order-of-magnitude estimates of selected reservoirs characteristcs based on hydrology and reservoir attributes.

Reservoir Attributes Volume, _ (m^3)Surface area, SA (km^2)Watershed area, DA (km^2)Length, L (km)Length of shoreline, L_sMean width, W (km), SA/LMaximum depth, Z_m (m)Mean depth, Z (m), _/SA**Order of Magnitude Estimates**Mean depth/maximum depth, Z/Z_mDrainage area/surface area, DA/SAAspect ratio, L/WShoreline development ratio Relative depth Areal erosion Residence time, _ (yr) _/*Q*

Densimetric Froude Number, Fd Single storm flushing ratio Depth at plunge point (m)

Note: Q = average annual total inflow (m^3/s)

Q_s = largest daily total inflow on record for May-Oct. (m^3/s)

_p = density difference between inflow and lake surface water (kg/m^3)

= density of surface water in lake (kg/m^3)

g = gravitational constant (9.8 m/s^2)

W_c = width of zone of conveyance at plunge point (m)

F_P = critical densimetric Froude number (assumed to be 0.4 based on literature)

Z_s = average Secchi depth (m)

Figure Legends

Figure 1. General categories and relationships among reservoirs environmental indicators. Management performance is compared with desired and achievable (reference) conditions.

Figure 2.

Figure 3. .

Figure 4. .